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DESIGN ASPECTS FOR STOCHASTIC COOLING SYSTEM COMPONENTS

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Abstract

The basic concepts and certain key parameters of stochastic cooling system hardware components are discussed. These components include pick-up, kickers, low noise and high power amplifiers as well as signal treatment aspects (e.g. notch filters, signal combiner boards). Examples of pick-up/kicker structures and concepts that have been implemented in different laboratories are shown. Important aspects are limitations imposed by the signal to noise ratio at the pick-up side as well as power limitations on the kicker side. In the signal transmission path there have been steady improvements with respect to enhanced noise figure of the preamplifiers, new filter technologies and better solid-state power amplifiers. Good diagnostics are mandatory for system tuning and optimization. A list of remaining challenges concludes this set of transparencies

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Design Aspects for Stochastic Cooling System Components

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- Pick-ups
- Low Noise Amplifiers
- Filters, Attenuators, Delays
- High Power Amplifiers
- Kickers
- Diagnostics
- Challenges
- Conclusion

Requirements for Pick-Ups

- If static, the aperture is dictated by the largest size of the beam, otherwise we may consider plunging devices
- We need an optimum sensitivity-bandwidth product per unit length, together with a minimum internal noise temperature
- Critical region: transverse sensitivity for beams with already small emittance and a small number of low charge state particles
- The charge state improves the signal power by a factor Z^2 as compared to (e.g.) protons

Types of Pick-ups

- Strip-line based structures such as the $\lambda/4$ or "loop " coupler, also "super-electrodes" = 2 $\lambda/4$ loops in series
- Printed structures known as printed loop coupler, patch antenna, slot-line coupler
- Periodic slot type coupler (major slot axis orthogonal to beam direction)
  - TEM-line with periodic slots (Faltin)
  - Wave-guide with periodic slots
- Traveling wave devices (FORWARD COUPLER !) for low β beams using strip-line sections with external (variable) delays
- Cerenkov and corrugated wall couplers (above 1 Ghz)

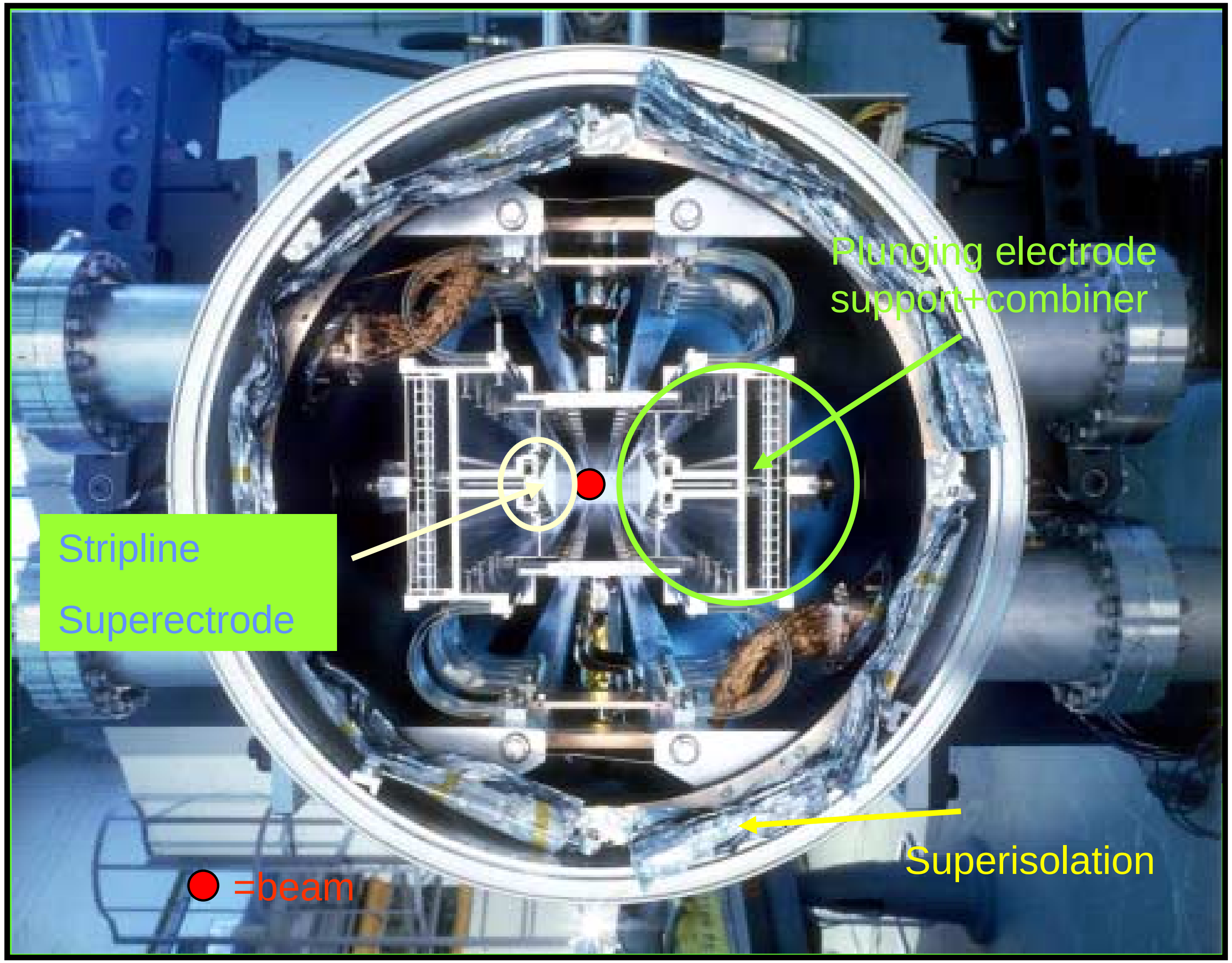
Pick-up design aspects for the range $0.4<\beta< 0.9$

- This is the transition region for strip-line like couplers to be used in the backward or forward coupling regime (for $v\approx c$ strip-line work only as backward couplers)
- Interest in using forward coupling since the coupling impedance scales~ to L^2 (L=length) of the structure, while for backward coupler the impedance is ~ L only
- The problem:Obtaining synchronism with the beam over a large relative bandwidth (several octaves desired) up to about 2 GHz.
- Avoid dielectric loading to slow down the phase velocity of a (long) strip-line (E/H ratio changing in wrong way)
- Inductive loading can do the job, but we have to watch for dispersion (perhaps a slotted strip-line with a corrugated ground-plane behind can do the job)

Cryo-cooling and/or plunging PUs?

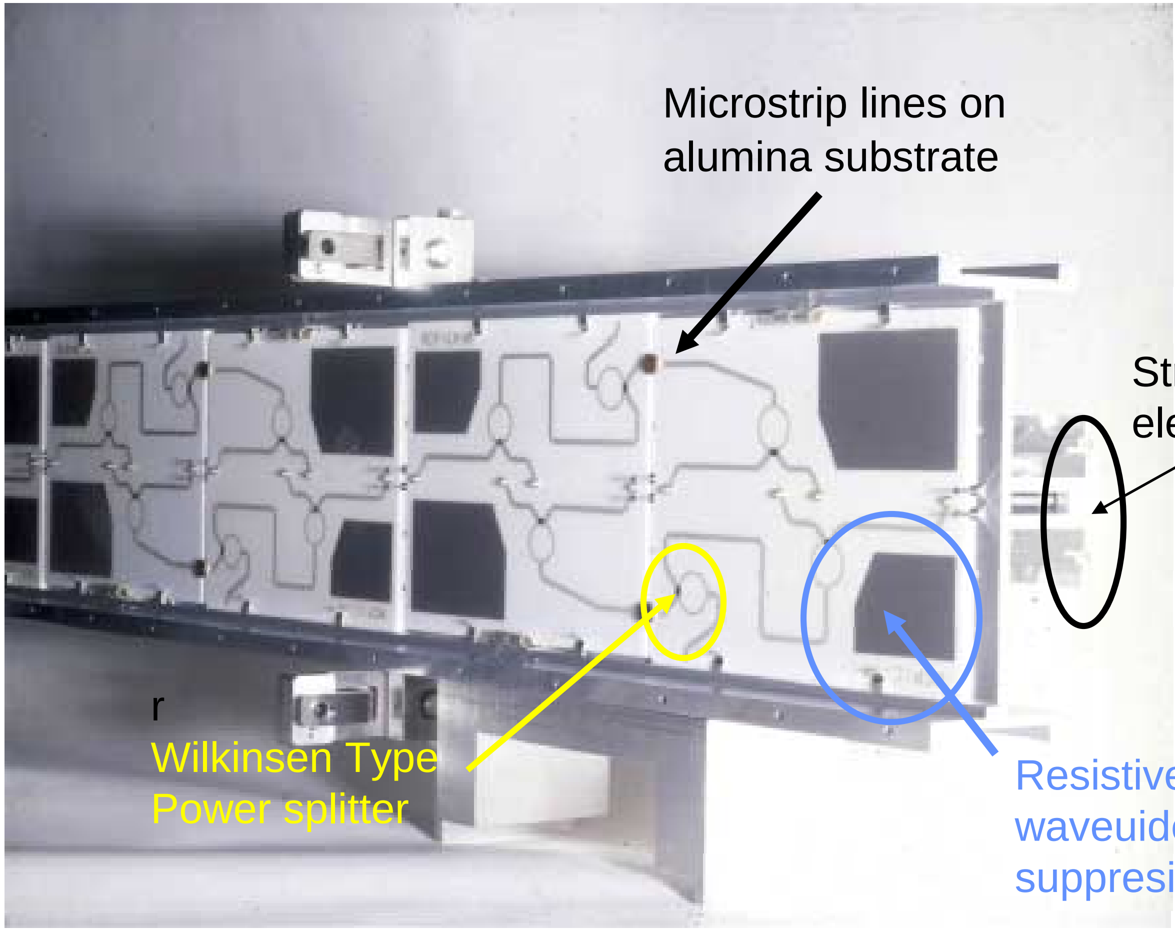
- Cryo-cooling certainly a way to reduce considerably the thermal originating from the pick-up structure. Examples:CERN AC, FNAL
- The effective noise temperature can be lowered down to a few deg K if needed.
- Since only the losses produce thermal noise, a very low loss structure (high Q cavity) can have an effective noise temperature of a few K , but staying physically at room temperature, when using an appropriate feedback technique and trading Q value against noise. [c.f. AD beam intensity monitor, F. Pedersen]
- Plunging is a very effective way to increase the transverse sensitivity (AC, AD) and can be used together with cryo-cooling (but its a mechanical challenge)

Example for a cryo-PU (CERN-AC)

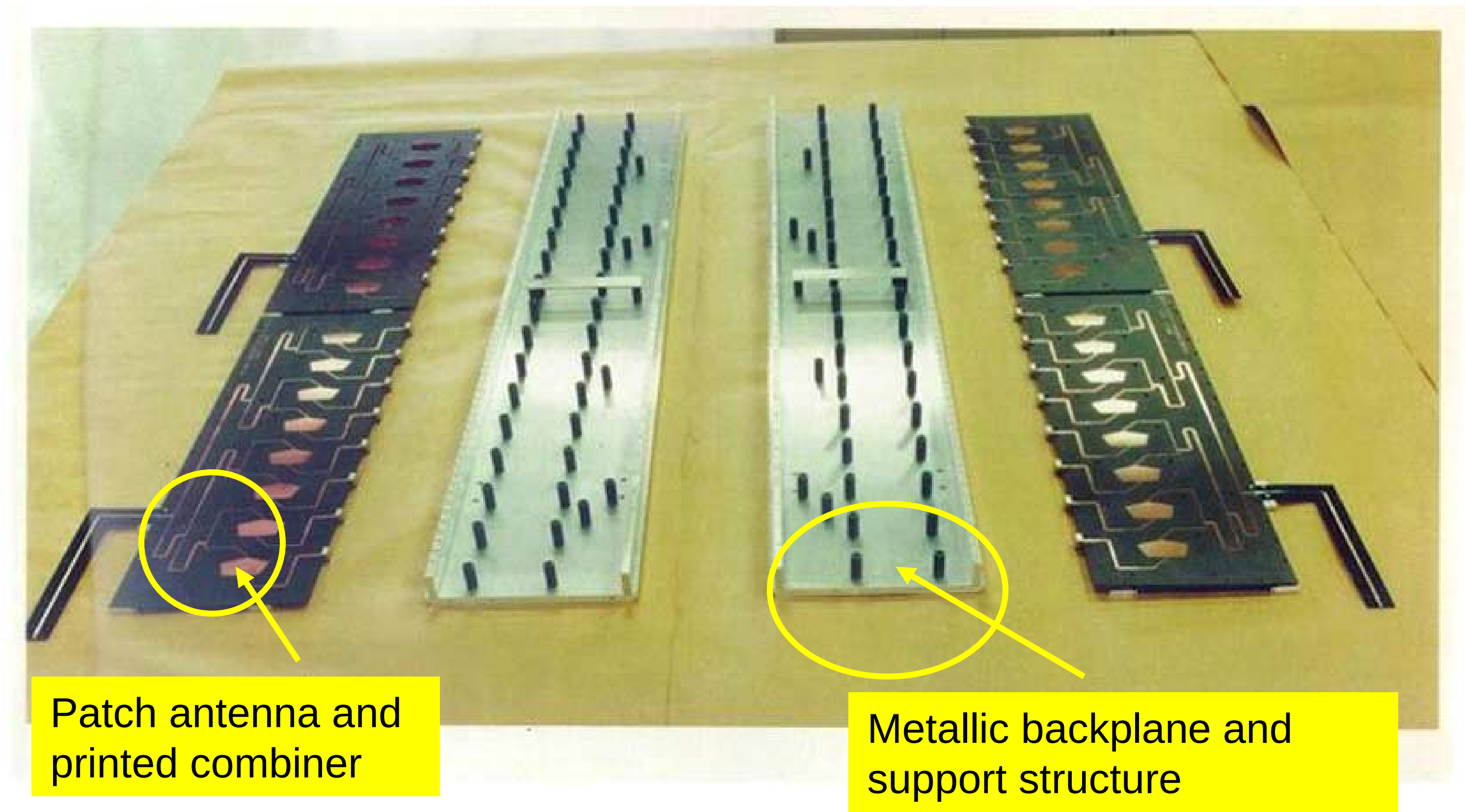


Picture rotated
by 90 deg

Combiner board of the CERN AC pick-ups

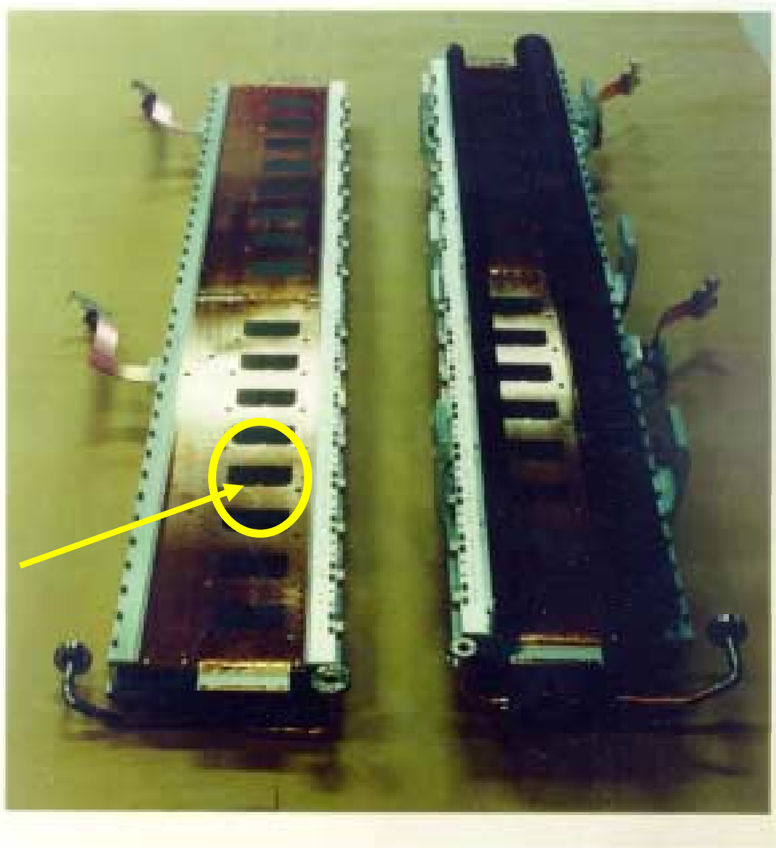


Example#1 of a printed loop coupler array (FNAL)



Example#2 of a printed loop coupler array (FNAL)

Printed 1-2 GHz coupler.Surfaces shown as seen by the beam



Behind these openings are the patch antennae

Low Noise Pre-amplifiers

- The present state of the art for preamplifiers is for
  - Un-cooled units I.e.at ambient temperature and 50 Ohm char. Impedance (input and output)
    Noise temperatures well below 70 K for frequencies above 50 MHz to <5 GHz with octave bandwidth and slightly worse with decade bandwidth or more
- Cryo-cooled amplifiers (usually GaAs, since the conduction mechanism in Si gets “frozen”) are usually better by a factor 2 or more than a comparable ambient operating version
- But caution is advised when installing a cryo-preamp directly in the UHV of a cryo-cooled PU tank (power dissipation, access for maintenance)

Signal combination and noise

- The signal combiner from different PU elements may be, due to its losses, an important source of signal/noise degradation, in particular, if the combiner is at ambient temperature
- Thus, if possible attribute to each PU electrode (or small group of electrodes) output its private, low noise preamp and then go into the combiner
- Using private preamps permits easy amplitude and phase adjustment (ampli on/off). They also have good output/input isolation
- Watch out for reasonably good out of band response of the combiner network

Noise Temperature Calculation

- The pick-up structure, together with its (50Ohm) termination, signal combiner and low noise preamplifiers is a network with inhomogeneous noise temperature distribution. Due to the presence of amplifiers it is non-reciprocal.
- Several techniques how to do the calculation:
  - #1 Assume that all lossy elements except one are at 0 K and work out its fractional noise contribution to the output port. Do that for all elements (superpos.)
  - #2 If the network is reciprocal assume a unit power fed into the output. Work out the fractional dissipation in each element.This returns the weighting function for each element, which has to be multiplied by its noise temperature and added up.

Filters, Attenuator, Delays (shopping list)

- Electronically variable attenuators (solid state), which should be phase–invariant (range 30-60 dB with 1 dB resolution)
- Variable (electronically or mechanically) delays (amplitude invariant !) from about 10 ps/step to ~1 ns.
- Gain equalizer (maybe variable) with defined phase.
- Phase equalizer (maybe variable) with defined gain
  don't forget Cauchy, not everything you want is permitted
- Δ-Σ hybrids with very good isolation, flatness and match
- Band-limiting filters with well defined out-of-band response and proper phase on the filter slopes

Notch Filters

- There are 4 basic versions:
- Classical coax delay line type, coaxial hybrid and long line phase dispersion + frequency dependent loss compensation
- Optical fiber based delay line.
  Watch out for dynamic range limitation by inter-modulation !
- Acoustic delay lines (bulk acoustic wave=BAW)
- Digital delay lines; very elegant for long delays but limitations wrt bandwidth, dynamic range(quantization)

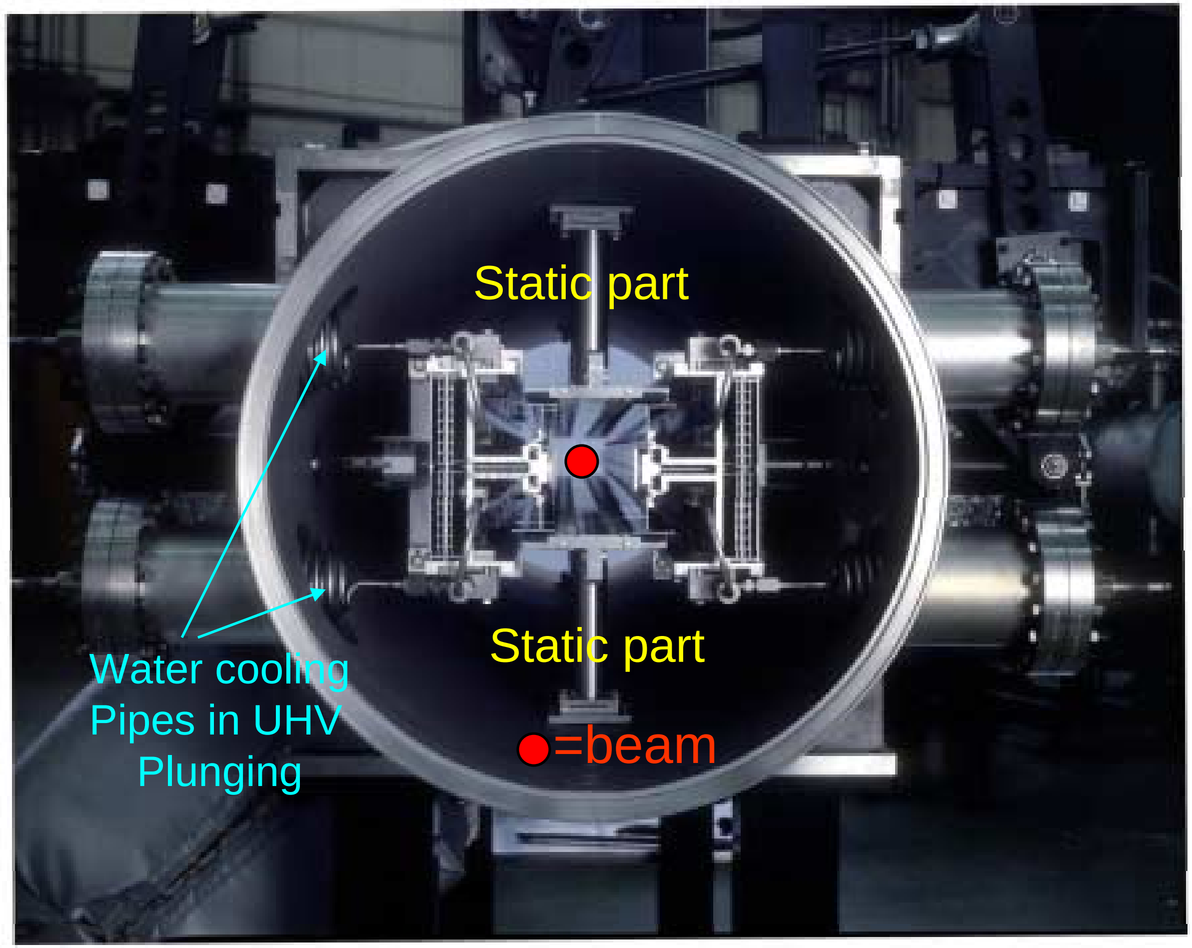
High Power Amplifiers

- 2 BASIC OPTIONS
  - Solid state class A:
    units with 100 Watt CW over an octave bandwidth are available up about 4 GHz. (often as water-cooled version in a <10 liter volume housing)
    This type of amplifier shows good performance wrt nonlinear properties (inter-modulation).
    No problems with amplitude dependent phase shift
  - TWT (traveling wave tube)
    can deliver more than 100 Watt over 2 octaves in the range 1-10 GHz.
    However many TWTs require internal or external feed-forward (feed-back) loops to compensate for (inherent) amplitude dependent phase shift and to minimize inter-modulation

Kickers

- Kickers are electro-magnetically equivalent to pick-ups, but not from the technological point of view
- They don't need cyro-cooling, but sometimes water-cooling is mandatory
- Plunging can help to reduce the transverse system power requirements, but is perhaps less important than for pick-ups, since most of the power is required when the beam has a large emittance.

Example for a kicker (CERN-AC)



Picture rotated by 90 deg

Diagnostics

- Murphy is everywhere, thus one can never have too much diagnostics
- Examples of beam-related diagnostics:
  - BTF (beam transfer function) measurements with a VNA (vector-network-analzyer) to check for correct gain and phase setting of the system
  - Cross-BTF to determine cross-talk (=heating) e.g. between a longitudinal and transverse system using the same Pus and/or kickers
  - RF power
  - Shielding effect (for optimum gain)
  - Non-destructive ε-evolution in all 3 planes vs time and intensity check (beam loss from cooling system)

Challenges

- How to do fast stacking
- We must somehow hide the stack from the injected beam
- There is the basic possibility of orbit separation in the PU and kicker region
- In the “old” AA a mechanically movable shutter was used
- The stack may be “hidden” in the minimum of a periodic notch-type filter possibly with time variant transmission properties during the stacking process
- Obviously a combination of all these tools is possible but not an easy task
- Can we overcome the rule to use only about 40% of the CW power from the (solid state) power amps

Conclusions

- The most difficult parts are sensitivity-bandwidth /unit length optimized pick-ups and kickers.
  - They must be very reliable
  - Possibly plunging
  - Excellent vacuum properties (incl bake-out, cryo)
- Components required for the signal transmission chain are usually available from the market, possibly as a custom defined product
  - But the devil is in the detail
  - Power amplifiers may become a large cost factor
- Careful estimation of ALL possible degrading effects is important and a certain contingency should be applied